

LONGITUDINAL SPIN TRANSFER TO Λ AND $\bar{\Lambda}$ IN POLARIZED PROTON-PROTON COLLISIONS AT $\sqrt{s} = 200$ GeV

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Abstract

We report our measurement on longitudinal spin transfer, D_{LL} , from high energy polarized protons to Λ and $\bar{\Lambda}$ hyperons in proton-proton collisions at $\sqrt{s} = 200$ GeV with the STAR detector at RHIC. The measurements cover Λ , $\bar{\Lambda}$ pseudorapidity $|\eta| < 1.2$ and transverse momenta, p_T , up to 4 GeV/ c . The longitudinal spin transfer is found to be $D_{LL} = -0.03 \pm 0.13(\text{stat}) \pm 0.04(\text{syst})$ for inclusive Λ and $D_{LL} = -0.12 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})$ for inclusive $\bar{\Lambda}$ hyperons with $\langle \eta \rangle = 0.5$ and $\langle p_T \rangle = 3.7$ GeV/ c . The p_T dependence of D_{LL} for positive and negative η is given.

The longitudinal polarization of Λ hyperons has been studied in e^+e^- annihilation and lepton-nucleon deep inelastic scattering (DIS) with polarized beams and/or targets. Such polarization studies provide access to polarized fragmentation function and the spin content of Λ [1]. Here we report the first measurement on longitudinal spin transfer (D_{LL}) from the proton beam to $\Lambda(\bar{\Lambda})$ produced in proton-proton collisions at $\sqrt{s}=200$ GeV [2],

$$D_{LL} \equiv \frac{\sigma_{p^+p \rightarrow \Lambda^+X} - \sigma_{p^+p \rightarrow \Lambda^-X}}{\sigma_{p^+p \rightarrow \Lambda^+X} + \sigma_{p^+p \rightarrow \Lambda^-X}}, \quad (1)$$

where the superscript $+$ or $-$ denotes the helicity. Within the factorization framework, the production cross sections are described in terms of calculable partonic cross sections and non-perturbative parton distribution and fragmentation functions. The production cross section has been measured for transverse momenta, p_T , up to about 5 GeV/ c and is well described by perturbative QCD evaluations [3]. The spin transfer D_{LL} is thus expected to be sensitive to polarized fragmentation function and helicity distribution function of nucleon, as reflected in different model predictions of D_{LL} at RHIC [4–7].

The spin transfer D_{LL} in Eq. (1) is equal to the polarization of Λ ($\bar{\Lambda}$) hyperons, $P_{\Lambda(\bar{\Lambda})}$, if the proton beam is fully polarized. $P_{\Lambda(\bar{\Lambda})}$ can be measured via the weak decay channel $\Lambda \rightarrow p\pi^-$ ($\bar{\Lambda} \rightarrow \bar{p}\pi^+$) from the angular distribution of the final state,

$$\frac{dN}{d \cos \theta^*} = \frac{\sigma \mathcal{L} A}{2} (1 + \alpha_{\Lambda(\bar{\Lambda})} P_{\Lambda(\bar{\Lambda})} \cos \theta^*), \quad (2)$$

where σ is the (differential) production cross section, \mathcal{L} is the integrated luminosity, A is the detector acceptance, which is in general a function of $\cos \theta^*$ as well as other observables, $\alpha_{\Lambda} = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$ [8] is the weak decay parameter, and θ^* is the angle between the $\Lambda(\bar{\Lambda})$ polarization direction and the (anti-)proton momentum in the Λ ($\bar{\Lambda}$) rest frame.

The data presented here were collected at the Relativistic Heavy Ion Collider (RHIC) with the Solenoidal Tracker at RHIC (STAR) [9] in the year 2005. An integrated luminosity of 2 pb⁻¹ was sampled with average longitudinal beam polarization of $52 \pm 3\%$ and

$48 \pm 3\%$ for two beams. The proton polarization was measured for each beam and each beam fill using Coulomb-Nuclear Interference (CNI) proton-carbon polarimeters [10]. Different beam spin configurations were used for successive beam bunches and the pattern was changed between beam fills. The data were sorted by beam spin configuration.

The analyzed data sample includes three different triggers. One is the minimum bias (MB) trigger sample, defined with a coincidence signal from Beam-Beam Counters (BBC) at both sides of STAR interaction region. The other data samples were recorded with the MB trigger condition and with two additional trigger conditions: a high-tower (HT) and a jet-patch (JP). The HT trigger condition required the BBC proton collision signal in coincidence with a transverse energy deposit $E_T > 2.6$ GeV in at least one Barrel Electromagnetic Calorimeter (BEMC) tower, covering $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$ in pseudorapidity η and azimuthal angle ϕ . The JP trigger condition imposed the MB condition in coincidence with an energy deposit $E_T > 6.5$ GeV in at least one of six BEMC patches each covering $\Delta\eta \times \Delta\phi = 1 \times 1$. The total BEMC coverage was $0 < \eta < 1$ and $0 < \phi < 2\pi$ in 2005.

The Λ ($\bar{\Lambda}$) candidates were identified from the topology of the weak decay channel to $p\pi^-$ ($\bar{p}\pi^+$), which has a branching ratio of 63.9% [8]. Charged particle tracks in the 0.5 T magnetic field were measured with the Time Projection Chamber (TPC), covering $0 < \phi < 2\pi$ and $|\eta| \lesssim 1.3$. The charge tracks after particle identification from specific energy loss dE/dx in TPC were paired to form a Λ ($\bar{\Lambda}$) candidate and topological selections were applied to reduce background [2, 3]. The selections included criteria for the distance of closest approach between the paired tracks and the distance between the point of closest approach and the beam collision vertex, and demanded that the momentum sum of the track pair pointed at the collision vertex. The criteria were tuned to preserve the signal while reducing the background fraction to 10% or less.

Figure 1(a) shows the invariant mass distribution for the Λ (filled circles) and $\bar{\Lambda}$ (open circles) candidates reconstructed from MB data with $|\eta| < 1.2$ and $0.3 < p_T < 3$ GeV/c. The mean values of the Λ and $\bar{\Lambda}$ mass distributions are in agreement with the PDG mass value $m_{\Lambda(\bar{\Lambda})} = 1.11568$ GeV/c² [8]. Figure 1(b) shows the same invariant mass distribution versus $\cos\theta^*$ for the Λ candidates. The number of Λ candidates varies with $\cos\theta^*$ because of detector acceptance. The small variation of the reconstructed invariant mass with $\cos\theta^*$ is understood to originate from detector resolution. In addition to signal, combinatorial background is seen as well as backgrounds of misidentified e^+e^- pairs at low invariant mass values near $\cos\theta^* = -1.0$ and of misidentified K_S^0 in a diagonal band at high invariant mass values and $\cos\theta^* > -0.2$. About 1.2×10^4 Λ and 1.0×10^4 $\bar{\Lambda}$ candidates from the

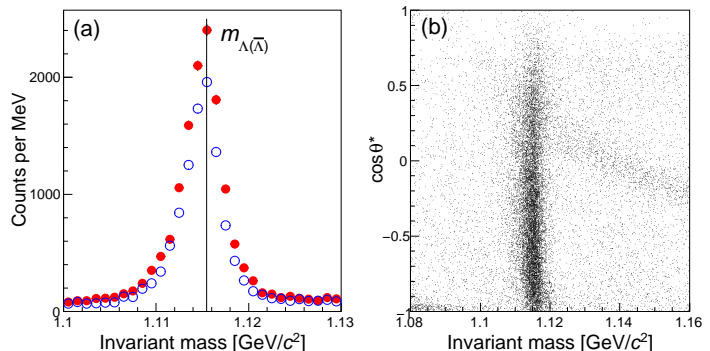


Figure 1. (a) The invariant mass distribution of Λ (filled circles) and $\bar{\Lambda}$ (open circles) candidates from reconstructed $p + \pi^-$ and $\bar{p} + \pi^+$ track pairs in 2005 MB data after topological selections. (b) The invariant mass distribution versus $\cos\theta^*$ for Λ .

MB sample were reconstructed in the invariant mass range $1.109 < m < 1.121 \text{ GeV}/c^2$ and were kept for further analysis.

To minimize the uncertainty associated with acceptance, the longitudinal spin transfer D_{LL} was extracted in small $\cos \theta^*$ intervals as follows:

$$D_{LL} = \frac{1}{\alpha P_{\text{beam}} \langle \cos \theta^* \rangle} \frac{N^+ - RN^-}{N^+ + RN^-}, \quad (3)$$

where P_{beam} is the beam polarization, N^+ (N^-) are the Λ ($\bar{\Lambda}$) counts in a small $\cos \theta^*$ interval when the beam is positively (negatively) polarized, $\langle \cos \theta^* \rangle$ is the average value in this $\cos \theta^*$ bin, and $R = L^+/L^-$ is the corresponding luminosity ratio for these two polarization states. Eq.(3) uses the parity conservation in the hyperon production in pp collisions, which leads to a sign flip of hyperon polarization when the beam helicity is flipped. The detector acceptance in a $\cos \theta^*$ interval is taken as a constant and thus canceled. For this measurement, only one polarized beam is needed. At RHIC both beams are polarized and the single spin yields N^+ (N^-) are thus formed from the yields n^{++} , n^{+-} , n^{-+} , and n^{--} by beam helicity configuration weighted with their corresponding relative luminosities. The luminosity ratios were measured with BBC at STAR [11].

The yields N^+ and N^- were determined for each $\cos \theta^*$ interval from the observed Λ and $\bar{\Lambda}$ candidate yields in the mass interval from 1.109 to 1.121 GeV/c^2 . The corresponding raw values D_{LL}^{raw} were averaged over 20 intervals covering the entire $\cos \theta^*$ range. The obtained D_{LL}^{raw} values and their statistical uncertainties were then corrected for (unpolarized) background dilution according to $D_{LL} = D_{LL}^{\text{raw}}/(1 - r)$, where r is the average background fraction. No significant spin transfer asymmetry was observed for the yields in the sideband mass intervals $1.094 < m < 1.103 \text{ GeV}/c^2$ and $1.127 < m < 1.136 \text{ GeV}/c^2$, and thus no further correction was applied to D_{LL} . However, a contribution was included in the estimated systematic uncertainty of the D_{LL} measurement to account for the possibility that the background could nevertheless be polarized.

The combined D_{LL} results from the MB data sample versus $\cos \theta^*$ are shown in Fig. 2(a) for Λ and Fig.2(b) for $\bar{\Lambda}$ hyperons with $0.3 < p_T < 3 \text{ GeV}/c$ and $0 < \eta < 1.2$ and $-1.2 < \eta < 0$. Positive η is defined along the direction of the incident polarized beam. Fewer than 50 counts were observed for $\cos \theta^* > 0.9$ and this interval was discarded for this reason. The extracted D_{LL} is constant with $\cos \theta^*$, as expected and confirmed by the quality of fit. In addition, a null-measurement was performed of the spin transfer for the spinless K_S^0 meson, which has a similar event topology. The K_S^0 candidate yields for $|\cos \theta^*| > 0.8$ were discarded since they have sizable $\Lambda(\bar{\Lambda})$ backgrounds. The result, δ_{LL} , obtained with an artificial weak decay parameter $\alpha_{K_S^0} = 1$, was found consistent with no spin transfer, as shown in Fig. 2(c).

The HT and JP data samples were recorded with trigger conditions that required large energy deposits in the BEMC, in addition to the MB condition. These triggers, however, did not require a highly energetic Λ or $\bar{\Lambda}$. To minimize the effects of this bias, the HT event sample was restricted to Λ or $\bar{\Lambda}$ candidates whose decay (anti-)proton track intersected a BEMC tower that fulfilled the trigger condition. About 50% of the $\bar{\Lambda}$ and only 3% of the Λ candidate events in the analysis pass this selection. This is qualitatively consistent with the annihilation of anti-protons in the BEMC. The $\bar{\Lambda}$ sample that was selected in this way thus directly triggered the experiment read-out. It contains about 1.0×10^4 $\bar{\Lambda}$ candidates with $1 < p_T < 5 \text{ GeV}/c$.

For the JP triggered sample, events were selected with at least one reconstructed jet that pointed to a triggered jet patch. The same jet reconstruction was used as in Ref. [12]. Jets outside the BEMC acceptance were rejected. The Λ and $\bar{\Lambda}$ candidates whose reconstructed η and ϕ fell within the jet cone of radius $r_{\text{cone}} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ were retained for further analysis. In most cases, the decay (anti-)proton track is part of the reconstructed jet, whereas the decay pion track is not. No correction was made to the jet finding and reconstruction for this effect. About 1.3×10^4 Λ and 2.1×10^4 $\bar{\Lambda}$ candidates with $1 < p_T < 5 \text{ GeV}/c$ remain after selections.

Figure 3 shows the D_{LL} results of Λ and $\bar{\Lambda}$ versus p_T for positive and negative η respectively. The $\bar{\Lambda}$ results from HT and JP data have been combined. No corrections have been applied for possible decay contributions from heavier baryonic states. The Λ and $\bar{\Lambda}$ results for D_{LL} are consistent with each other and consistent with no spin transfer from the polarized proton beam to the produced Λ and $\bar{\Lambda}$ to within the present uncertainties. The data have p_T up to $4 \text{ GeV}/c$, where $D_{LL} = -0.03 \pm 0.13(\text{stat}) \pm 0.04(\text{syst})$ for the Λ and $D_{LL} = -0.12 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})$ for the $\bar{\Lambda}$ at $\langle\eta\rangle = 0.5$. For reference, the model predictions of Refs. [4, 7], evaluated at $\eta = \pm 0.5$ and $p_T = 4 \text{ GeV}/c$, are shown as horizontal lines. The expectations of Ref. [4] hold for Λ and $\bar{\Lambda}$ combined and examine different polarized fragmentation scenarios, in which the strange (anti-)quark carries all or only part of the Λ ($\bar{\Lambda}$) spin. The model in Ref. [7] separates Λ from $\bar{\Lambda}$ and otherwise distinguishes the direct production of the Λ and $\bar{\Lambda}$ from the (anti-)quark in the hard scattering and the indirect production via decay of heavier (anti-)hyperons. The evaluations are consistent with the present data and span a range of values that, for positive η , is similar to the experimental uncertainties. The values for negative η are expected to be negligible and thus less sensitive [4, 7]. The current experimental uncertainties are statistics limited, and we expect future data be able to distinguish between different models of polarized fragmentation and parton distribution functions.

The total systematic uncertainty in D_{LL} is varying from 0.02 to 0.04 with increasing p_T and is smaller than the statistical uncertainty, ranging from 0.06 to 0.14, for each of the data points. In estimating the size of the systematic uncertainties, we have combined contributions from the uncertainties in decay parameter α and in the measurements of the proton beam polarization and relative luminosity ratios, as well as uncertainty caused by the aforementioned backgrounds, overlapping events (pile-up), and, in the case of the

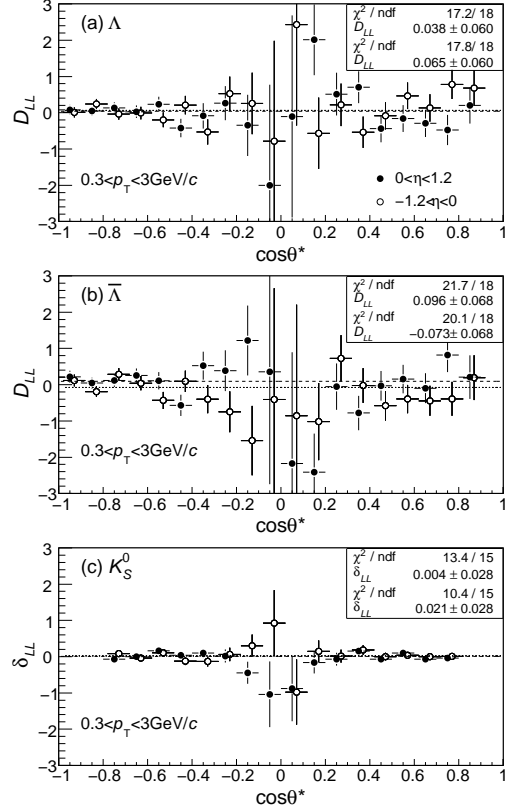


Figure 2. The spin transfer D_{LL} versus $\cos\theta^*$ for (a) Λ and (b) $\bar{\Lambda}$, and (c) the spin asymmetry δ_{LL} for the control sample of K_S^0 mesons versus $\cos\theta^*$. Only statistical uncertainties are shown. The data points with negative η have been shifted slightly in $\cos\theta^*$ for clarity.

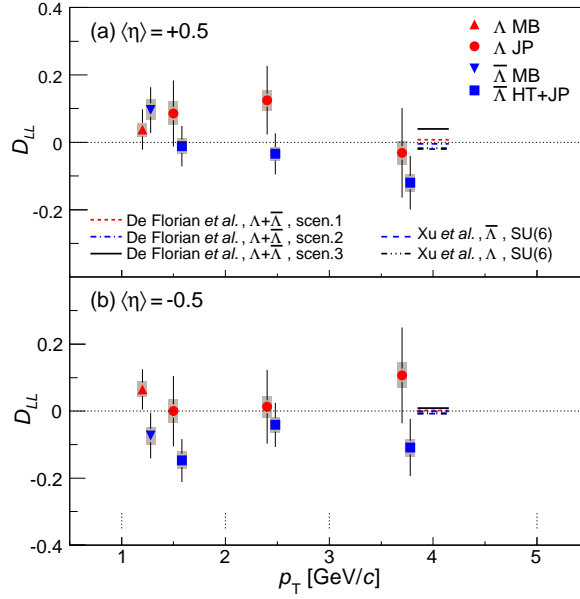


Figure 3. (Color online) Comparison of Λ and $\bar{\Lambda}$ spin transfer D_{LL} in polarized proton-proton collisions at $\sqrt{s} = 200$ GeV for (a) positive and (b) negative η versus p_T . The vertical bars and bands indicate the sizes of the statistical and systematic uncertainties, respectively. The $\bar{\Lambda}$ data points have been shifted slightly in p_T for clarity. The dotted vertical lines indicate the p_T intervals in the analysis of HT and JP data. The horizontal lines show model predictions.

JP sample, trigger bias studied with Monte Carlo simulation [2]. The effect of Λ ($\bar{\Lambda}$) spin precession in the STAR magnetic field is negligible.

In addition to longitudinal spin transfer, the transverse spin transfer of hyperons from proton is also of particular interest in pp collisions, since it can provide access to the transverse spin content of nucleon, i.e., the transversity distribution, which is still poorly known in experiment. Unlike the polarization is along hyperon's momentum in the case of longitudinal polarization, the azimuthal direction in the transverse plane needs to be determined first to measure transverse hyperon polarization. E704 experiment measured the transverse spin transfer D_{NN} with respect to the production plane [13]. Another choice is to first determine the transverse polarization direction of the fragmenting parton in a hard scattering, which is different from the polarization direction before the scattering, but can be determined by a rotation around the normal of the scattering plane [14]. The fragmenting parton's axis can be obtained via jet reconstruction with charged particle and energy deposits in calorimeters. Then along this direction, the transverse hyperon polarization, and thus the transverse spin transfer D_{TT} can be measured. The transverse polarization of Λ ($\bar{\Lambda}$) is being investigated with hyperons reconstructed at mid-pseudorapidities with TPC at STAR. Sizable transverse spin transfer effect is expected to exist in the large $x_F (\equiv 2p_z/\sqrt{s})$ region. At STAR, a Forward Hadron Calorimeter (FHC) is being proposed to be installed behind the Forward Meson Spectrometer (FMS) in the near future, which may enable the reconstruction of Λ hyperons via the decay channel to $n\pi^0$ with π^0 detected by the FMS and n by the FHC. Simulation studies on Λ reconstruction in the forward region using the FMS and the FHC are underway.

In summary, we made measurements on the longitudinal spin transfer to Λ and $\bar{\Lambda}$ hyperons in $\sqrt{s} = 200$ GeV polarized proton-proton collisions for hyperon p_T up to 4 GeV/ c . The spin transfer is found to be $D_{LL} = -0.03 \pm 0.13(\text{stat}) \pm 0.04(\text{syst})$ for Λ and $D_{LL} = -0.12 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})$ for $\bar{\Lambda}$ hyperons with $\langle \eta \rangle = 0.5$ and $\langle p_T \rangle = 3.7$ GeV/ c . The measurements of the transfer spin transfer may provide access to transversity distribution of the nucleon, and feasibility studies have started.

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